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EFFECT OF WELL SCREENS ON FLOW INTO WELLS

by Jack S. Petersen, Carl Rohwer, M. ASCE,
M. L. Albertson, J.M. ASCE

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EFFECT OF WELL SCREENS ON FLOW INTO WELLS

By Jack S. Petersen,[1] Carl Rohwer,[2] M. ASCE, and M. L. Albertson,[3] J. M. ASCE

[1] Graduate Student, Univ. of Missouri, Columbia, Mo.
[2] Senior Irrig. Engr., Div. of Irrig. and Water Conservation, SCS, USDA, Ft. Collins, Colo.
[3] Prof. of Civ. Eng. and Head of Fluid Mechanics Research, Colorado Agri. and Mech. College, Ft. Collins, Colo.

Synopsis

The hydraulics of wells involves flow (1) in the surrounding aquifer, (2) through the well screen, and (3) inside the well. This paper is concerned with the flow through the screen and inside the well. A theoretical development is presented which relates the loss of head to the characteristics of the well screen. To support the theoretical development, a laboratory investigation of well screens was made.

The objective of the investigation was to establish criteria which could be used to aid in the selection of well screens to meet the varied conditions found throughout the United States. To do this, screen coefficients (permitting the use of a theoretical equation for design purposes) were determined for specific well screens.

Introduction

The increasing demand for domestic, industrial, and irrigation water in the United States has made necessary the development of ground-water resources to supplement surface supplies. The importance of wells is not limited to water supply, however, since wells have been found to be an effective aid in solving drainage problems. The essential feature of ground-water development (whether for water supply or for drainage) is the installation of ground-water wells. Installing a well consists of digging a hole into a water-bearing formation, placing a casing or screen in the hole to support the surrounding aquifer, and setting the pump. The quantity of water that can be obtained from a well depends primarily on the characteristics of the underground reservoir which cannot be changed by the engineer. For any specific location, however, the quantity and cost of water depends on the efficiency of the well system and the pumping plant. Since these efficiencies are determined by factors over which the engineer has some control, research dealing with such factors is important in the establishment of better design criteria and development methods.

Although many elements are involved in the construction of wells, one of the difficulties encountered is the selection of the well screen to meet the specific needs and conditions found at the well site. The basic requirements for any well screen are that it (1) be resistant to corrosion and deterioration, (2) be structurally strong enough to prevent collapse, (3) prevent excessive movement of sand into the well, and (4) have a minimum resistance to the flow of water

into the well. An efficient screen must represent a compromise of several desirable characteristics. For example, a screen with a large percentage of open area will provide a lower resistance to flow into the well, but it will have less structural strength and will permit more pumping of sand than a screen with a smaller percentage of open area. The characteristics of the well screen and the characteristics of the surrounding media influence the pattern of inflow and the losses. The importance of each characteristic must be evaluated for the particular field conditions existing at the location of the well.

The investigation reported on herein has been confined to the hydraulic characteristics of various types of well screens and the porous media immediately surrounding the screens. From such an investigation it is possible to design for the basic requirement of minimum head loss. Although this study was confined to water wells, the theoretical analysis is general for any liquid, and the results obtained should be applicable to other liquids of low viscosity.

Since there are few investigations of well screens, the selection of a proper screen is usually a matter of engineering judgment and experience. A criterion proposed by E. W. Bennison is that a velocity of less than from 0.1 ft per sec to 0.25 ft per sec through the individual screen openings will keep sand movement and head losses to a minimum.[4] A significant observation was made by G. L. Corey concerning the percentage of open area of a screen.[5] Mr. Corey stated that there is a critical percentage of open area above which the head losses are no longer a function of the open area. Criteria for drainage wells have been established by the Corps of Engineers, United States Department of the Army.[6] These criteria provide a relationship—between the gravel in the gravel envelope and the size of the particles in the surrounding formation—which will meet the permeability and stability requirements. Relationships were also determined for the size of screen openings to be used with a specific size of gravel filter.

A satisfactory study of the head losses resulting from flow into a well must include experimental work conducted in the laboratory or in the field. As in most problems in hydraulics, however, a theoretical analysis of the problem is desirable as a guide to experimental work. Some phases of the experimental work can be shortened (with adequate analysis) to that which is necessary to validate the theory; the investigation described herein was conducted with this idea in mind. The various factors involved in the flow into and through a screen were related theoretically. Tests were performed on idealized well screens to establish the validity of the theory; then commercial well screens were tested to determine screen coefficients that would permit the use of theoretical equations for the determination of head loss to be expected (in the field) when a given combination of screen and gravel envelope was used.

[4] "Ground Water," by E. W. Bennison, Edward E. Johnson, Inc., St. Paul, Minn., 1947, p. 509.

[5] "Hydraulic Properties of Well Screens," by G. L. Corey, thesis presented to Colorado Agri. and Mech. College, at Ft. Collins, Colo., in 1949, in partial fulfilment of the requirement for the degree of Master of Science.

[6] "Field and Laboratory Investigations of Design Criteria for Drainage Wells," *Technical Memorandum No. 195-1*, U. S. Waterways Experiment Station, Vicksburg, Miss., 1942, p. 78.

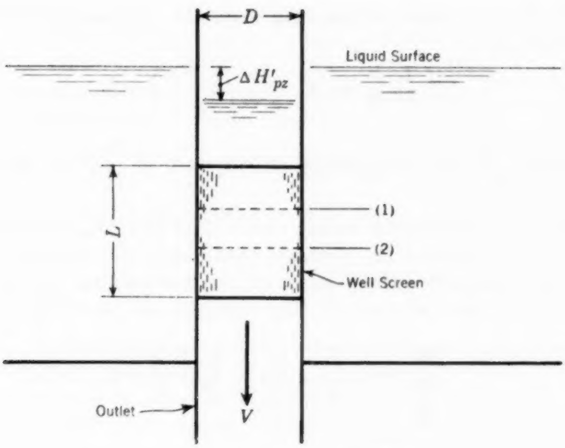


Fig. 1.—Definition Sketch

Theoretical Development

The problem of flow into and through well screens can be considered to be flow through a series of orifice openings as the water enters the screen, and to be flow within a pipe manifold as it moves along the axis of the screen. As the water enters the screen through the openings, a conversion of potential energy to kinetic energy is necessary to develop the jet velocity. A dissipation of the jet energy then occurs, which can be assumed to be complete. That is, the kinetic energy of the jet is not recovered as either potential or kinetic energy. The water then accelerates in a direction parallel to the center line of the screen. The acceleration results in a change of the momentum flux.

The theoretical analysis will be made for a screen contained in a large body of liquid where the flow inside the screen is downward. A definition sketch is shown in Fig. 1, in which the origin or zero length is at the top of the perforated section. As a first approach to a solution, an analysis will be made for a screen surrounded only by a liquid—the effect of the surrounding gravel being eliminated from consideration.

The loss of head caused by flow through a well screen depends on the characteristics of the screen geometry, the fluid, and the flow. The variables of greatest importance involved in the problem are: (1) The screen length, L; (2) the screen diameter, D; (3) the percentage of open area, A_p; (4) the coefficient of contraction for the openings, C_c; (5) the internal roughness of the well screen, k; (6) the difference in pressure between the inside and outside of the screen, Δp; (7) the velocity of the liquid in the well screen, V; (8) the mass density of the fluid, ρ; and (9) the coefficient of dynamic viscosity, μ. The variables can be expressed in the following relationship:

$$f_1 (L, D, \Delta p, k, \rho, \mu, V, A_p, C_c) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

If D, ρ, and V are chosen as repeating variables, a dimensional analysis will yield the function,

$$f_2\left(\frac{L}{D}, \frac{k}{D}, A_p, C_c, \frac{\Delta p}{\rho V^2}, \frac{V D \rho}{\mu}\right) = 0 \quad \text{(2)}$$

The parameter $\frac{\Delta p}{\rho V^2}$ can be arranged in the form of $\frac{\Delta h_{pz}}{\frac{V^2}{g}}$ by multiplying by γ/γ, in which γ is the specific weight of the fluid and Δh_{pz} is the difference in piezometric head between the pressure inside and the pressure outside the screen. This is justified if the pressure drop is assumed to take place between two points at the same elevation. The function can be written in the form,

$$\frac{\Delta h_{pz}}{\frac{V^2}{g}} = f_3\left(C_c, A_p, \frac{L}{D}, \frac{k}{D}, \frac{V D \rho}{\mu}\right) \quad \text{(3)}$$

Because the effects of viscosity are of secondary importance, the Reynolds number can be eliminated from consideration as a first approximation. Furthermore, the drag inside the well screen is almost entirely the result of the influence of the jets issuing from the screen openings, and therefore the roughness parameter can be neglected. With these simplifications, Eq. 3 reduces to

$$\frac{\Delta h_{pz}}{\frac{V^2}{g}} = f_4\left(C_c, A_p, \frac{L}{D}\right) \quad \text{(4)}$$

When the screen is surrounded by gravel, several additional factors enter the problem. These factors include the size of the openings in relation to the size of the gravel, the size of the gravel relative to the diameter of the screen, and the standard deviation of the gravel.

Without additional knowledge of the phenomenon, Eq. 4 must be evaluated experimentally. It is possible, however, to analyze the problem further by a theoretical treatment.

An analysis of the problem can be made by applying the principles of continuity, energy, and momentum. The usual forms for these relationships, assuming (1) no acceleration normal to the direction of flow, (2) no variation in the velocity across the sections considered, and (3) no resistance to flow, are

$$Q = V_1 A_1 = V_2 A_2 \quad \text{(5a)}$$

$$\frac{V^2_1}{2g} + \frac{P_1}{\gamma} + z_1 = \frac{V^2_2}{2g} + \frac{P_2}{\gamma} + z_2 \quad \text{(5b)}$$

and

$$F_y = \rho\,(Q_1 V_1 - Q_2 V_2)_y \quad \text{(5c)}$$

in which Q is the rate of flow parallel to the screen axis, A denotes the cross-sectional area of the well screen, g is the gravitational acceleration, $\frac{P}{\gamma}$ denotes

the hydrostatic head, ρ is the density, z is the distance from a datum, F_y denotes the change in momentum along axis of screen between the indicated points, and the subscripts 1 and 2 correspond to the sections shown in Fig. 1.

The increment of discharge dQ, through an increment of length dL, can be shown by the energy and continuity equations to be

$$dQ = C_c\, A_p\, \pi\, D\, \sqrt{2\, g\, \Delta h_{pz}}\, dL \qquad (6)$$

By integrating Eq. 6 the total discharge into the screen is

$$Q = C_c\, A_p\, \pi\, D\, \sqrt{2\, g} \int \sqrt{\Delta h_{pz}}\, dL \qquad (7)$$

in which Δh_{pz} is the difference in head between the inside and outside of the screen in the increment of length dL.

The momentum equation can be applied to the flow within the pipe (between sections 1 and 2) to give the equation,

$$A\, \gamma\, (h_{pz,1} - h_{pz,2}) = -\, \rho\, (Q_1\, V_1 - Q_2\, V_2) \qquad (8a)$$

which can be written in differential form as

$$-\, A^2\, g\, \Delta h_{pz} = d(Q^2) \qquad (8b)$$

in which h_{pz} is the piezometric head within the screen. If the piezometric head on the entire outside surface is constant,

$$\Delta h_{pz} = -\, h_{pz} \qquad (9a)$$

and

$$d(\Delta h_{pz}) = -\, \Delta h_{pz} \qquad (9b)$$

This permits Eq. 8*b* to be written as

$$d(Q^2) = A_2\, g\, d(\Delta h_{pz}) \qquad (10a)$$

Integrating Eq. 10*a* results in

$$Q^2 = A^2\, g\, \Delta h_{pz} + C_1 \qquad (10b)$$

Since Δh_{pz} is equal to $\Delta h'_{pz}$ when Q equals zero,

$$C_1 = -\, A^2\, g\, \Delta h'_{pz} \qquad (11)$$

in which $\Delta h'_{pz}$ is the difference in piezometric head between the inside and outside of the screen at the point where L equals zero. Eq. 10*b* can be written as

$$Q^2 = A^2\, g\, (\Delta h_{pz} - \Delta h'_{pz}) \qquad (12)$$

Differentiating Eq. 12 with respect to the length L results in

$$\frac{dQ}{dL} = \frac{A^2\, g}{2\, Q}\, \frac{d(\Delta h_{pz})}{dL} \qquad (13)$$

When Eqs. 6, 12, and 13 are combined into the dimensionless relationship,

$$\frac{2\, C_c\, A_p\, \pi\, D\, \sqrt{2\,g}\, dL}{\sqrt{g}\, A^2} = \frac{d(\Delta h_{pz})}{\sqrt{(\Delta h_{pz})^2 - \Delta h_{pz}\, \Delta h'_{pz}}} \quad \text{(14a)}$$

or

$$\frac{C}{D}\, dL = \frac{d(\Delta h_{pz})}{\sqrt{(\Delta h_{pz})^2 - \Delta h_{pz}\, \Delta h'_{pz}}} \quad \text{(14b)}$$

integration of Eq. 14*b* yields

$$C\, \frac{L}{D} = \cosh^{-1}\left(\frac{2\, \Delta h_{pz} - \Delta h'_{pz}}{\Delta h'_{pz}}\right) + C_2 \quad \text{(14c)}$$

in which

$$C = 11.31\, C_c\, A_p \quad \text{(14d)}$$

The constant of integration C_2 equals zero, since Δh_{pz} equals $\Delta h'_{pz}$ when L is equal to zero. Replacing $\Delta h'_{pz}$ with its value from Eq. 12, Eq. 14*c* can be reduced to the form:

$$\frac{\Delta h_{pz}}{\dfrac{Q^2}{A^2\, g}} = \frac{\cosh\left(\dfrac{C\,L}{D} + 1\right)}{\cosh\left(\dfrac{C\,L}{D} - 1\right)} \quad \text{(15)}$$

or in terms of the velocity

$$\frac{\Delta h_{pz}}{\dfrac{V^2}{2\,g}} = 2\, \frac{\cosh\left(\dfrac{C\,L}{D} + 1\right)}{\cosh\left(\dfrac{C\,L}{D} - 1\right)} \quad \text{(16)}$$

Eq. 15 is a specific relationship that combines the dimensionless parameters C_c, A_p, and L/D into a single variable.

A laboratory investigation of the problem can be made with Eq. 15 as a basis for the study. The experimental results would be expected to follow this theoretical equation in some manner. Deviations would exist where the effect of the variables eliminated from Eq. 3 become important; that is, when the effect of the Reynolds number and the roughness parameter become significant. Additional deviations could occur as a result of the assumptions made in deriving Eq. 15. The more important of these assumptions are as follows:

1. The velocity variation is small across any section inside the screen.
2. The piezometric head on the outside of the screen is constant over the entire outside surface of the screen.
3. The kinetic energy of the jet entering the screen is not recovered as either potential energy or usable kinetic energy.

The two dimensionless numbers involved in Eq. 15 $\left(\dfrac{\Delta h_{pz}}{Q^2/A^2\, g} \text{ and } \dfrac{C\,L}{D}\right)$ can be plotted to give the theoretical curve shown in Fig. 2. As shown by the theoretical curve, the loss coefficient $\left(\dfrac{\Delta h_{pz}}{Q^2/A^2\, g}\right)$ becomes nearly constant

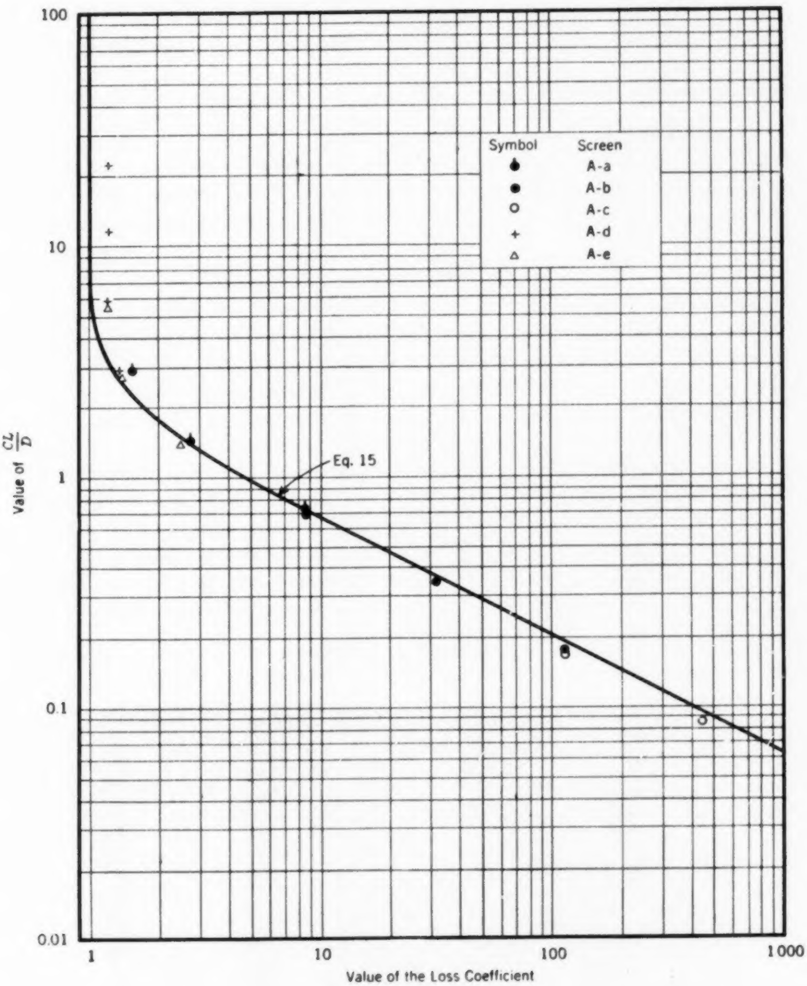


FIG. 2.—LOSS COEFFICIENT AS A FUNCTION OF $\frac{CL}{D}$ FOR TYPE A SCREENS

when the hyperbolic cosine of $\frac{C\,L}{D}$ is large, so that the plus or minus 1 is insignificant. The curve becomes asymptotic to a loss coefficient equal to unity, but for practical purposes the loss coefficient equals unity for all values of $\frac{C\,L}{D}$ greater than 6. Since the loss coefficient is a measure of the loss, the loss is a minimum when the parameter is a minimum. The value of $\frac{C\,L}{D}$ can be made larger than the critical value of 6 by increasing C_c, A_p, and L, or by decreasing D—that is, the percentage of open area of the screen for the head loss to be a minimum depends on the length and diameter of the screen. However, it should be noted that decreasing D also decreases A and consequently increases Δh_{pz}.

Experimental Equipment and Procedure

To determine the validity of Eq. 15, values of the variables involved had to be determined either by actual measurements or by criteria that had been shown to be valid. For this study a set of idealized screens, fabricated in the laboratory, was used. The word "idealized" is used to differentiate between screens constructed in the laboratory and commercially manufactured screens. These screens were constructed from flat sheet metal, and round holes were drilled in the metal on uniformly spaced centers. Protrusions from the holes were filed off, and the holes were reamed to remove any burrs. With this procedure the holes approached the conditions required for a sharp-edged orifice and permitted the use of the contraction coefficients determined theoretically by R. von Mises for two-dimensional flow.[7] The perforated sheets were then rolled into a cylinder and the edges welded together to form a well screen. The spacing and diameter of the holes and the diameter and length of the screens were

[7] "Elementary Mechanics of Fluids," by Hunter Rouse, John Wiley & Sons, Inc., New York, N. Y., 1946.

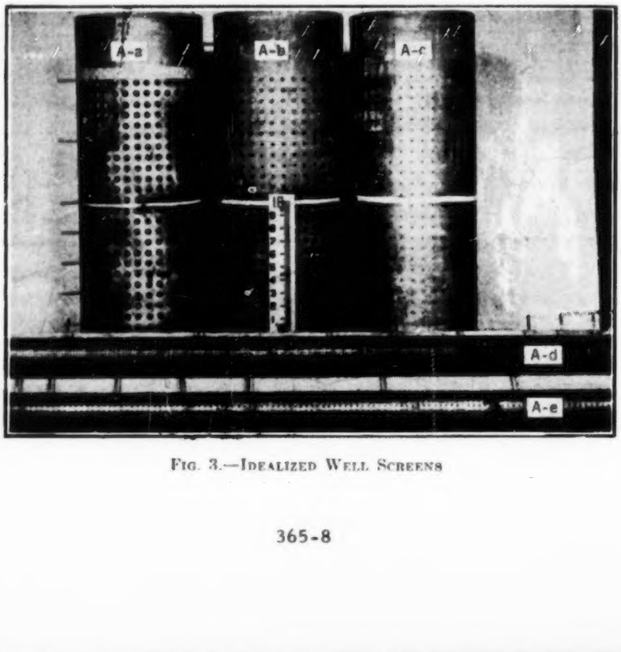


Fig. 3.—Idealized Well Screens

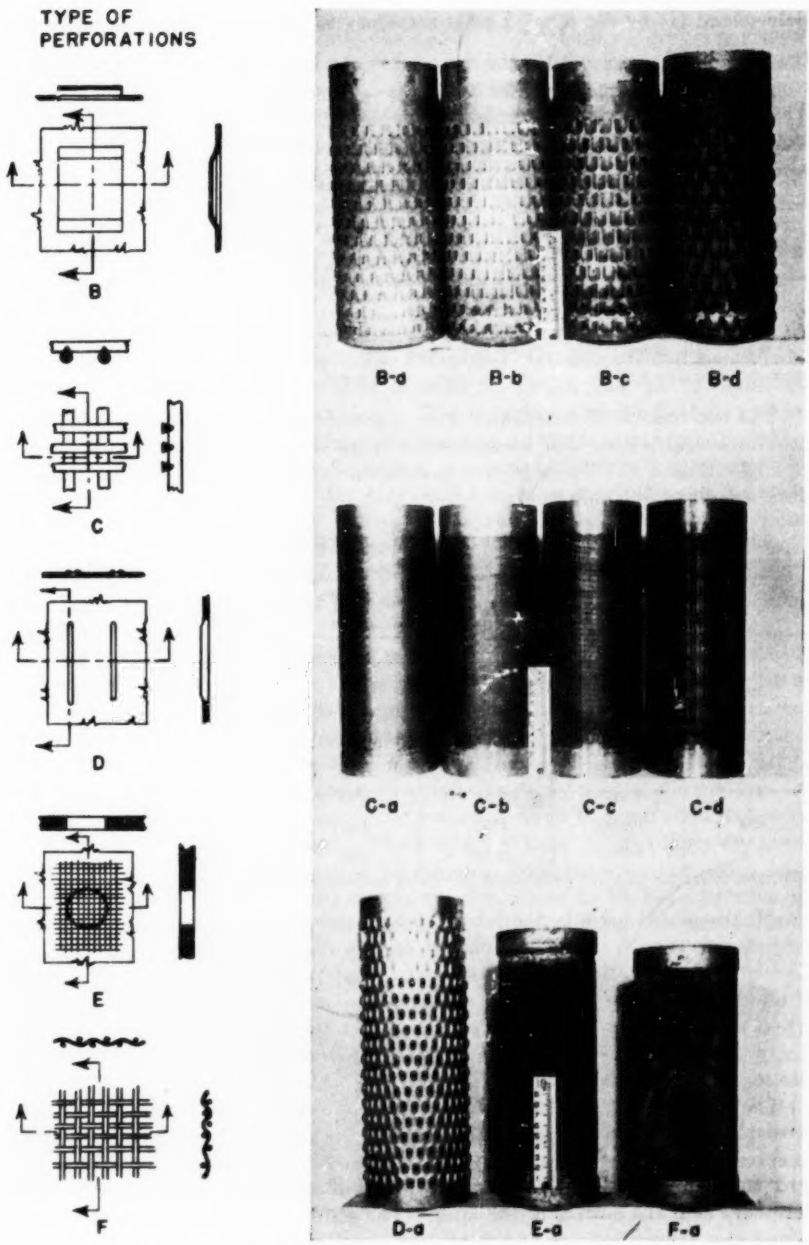


FIG. 4.—COMMERCIAL WELL SCREENS

determined (1) by the $\left(\frac{C\,L}{D}\right)$-ratio necessary to cover the practical range of the theoretical curve and (2) the desirability of having data on these screens for conditions comparable to those of the commercial screens that were tested. These screens designated type A screens, are shown in Fig. 3. Dimensions of the screens are presented in Table 1.

TABLE 1.—DIMENSIONS OF IDEALIZED SCREENS

Screen	Screen diameter, in feet	Hole diameter, in inches	Screen length, in feet	Hole spacing on centers, in inches	Percent of open area	Screen thickness, in inches
A-a	1.008	½	2.00	1	19.63	0.045
A-b	1.008	¼	2.00	1	4.93	0.045
A-c	1.008	⅛	2.00	1	1.23	0.020
A-d	0.252	⅛	4.00	¼	19.71	0.020
A-e	0.252	⅛	4.00	½	4.93	0.020

The commercial screens tested were representative of the types commonly used in actual wells. For identification these screens were designated types B, C, D, E, and F. These screens are shown in Fig. 4; the important dimensions are given in Table 2.

TABLE 2.—DIMENSIONS OF COMMERCIAL SCREENS

Screen	Screen diameter, in feet	Slot width, in inches	Screen length, in feet	Percent of open area	Screen thickness, in inches
B-a	0.9804	1/16	2.07	3.46	0.080
B-b	0.9804	1/8	2.02	7.15	0.080
B-c	0.9804	3/16	2.09	11.23	0.080
B-d	0.9804	1/4	2.09	14.62	0.080
C-a	0.9054	0.020	2.03	18.18	9/64
C-b	0.9054	0.040	2.00	30.76	9/64
C-c	0.9054	0.100	2.01	52.63	9/64
C-d	0.9054	0.200	2.03	68.96	9/64
D-a	0.9804	1/8	2.00	4.77	0.080
E-a	0.8419	1/2	2.00	14.75	11/32
F-a	0.9231	0.145	2.00	33.64	1/4

All the gravel used in these tests was river-bed material which had been subjected to stream action long enough for the sharp edges to be eroded away. Each size of gravel was screened so that the particles passed through a screen of one size and were retained on a screen of a smaller size. The five sizes of gravel used and the results of the sieve analyses are shown in Fig. 5. The 50% size of the gravel (as shown by the sieve analysis) was used as the representative size required for the analysis of test data.

The laboratory apparatus (shown in Fig. 6) used for testing the well screens consisted of a cylindrical steel tank installed in a recirculating system. The steel testing tank was 7.5 ft in diameter and 6 ft in depth. Water entered the tank through a diffusion ring which distributed the water equally around the periphery near the bottom of the tank. The water level in the tank was maintained at a constant depth of 5 ft by two overflow pipes installed in the inside of the tank. Flow through the screen was controlled by a valve on the pipe

carrying the water from the tank to the weir box. To hold the gravel envelope in place a heavy wire screen 30 in. in diameter and 6 ft long was placed around the well screen. The water was pumped from a sump through an 8-in.-diameter pipe to the tank. From the tank the water passed (by gravity flow) through the test screens located at the center of the tank and then downward through an outlet pipe to a weir box. From the weir box the water spilled into a return channel connected to the sump of the pump.

The differences in piezometric head were determined by hook gages set in stilling wells. The hook-gage readings could be made to one-thousandth of a foot and it was possible to estimate the readings to the nearest five ten-thousandths of a foot.

Extensions to the screens were made by joining an unperforated length of casing to each end of the screen. The extensions on the upper end were made to permit a substantial loss of head through the screen and still to maintain submerged flow through the openings. The extensions on the bottom end of the screen were made to bring the perforated area to the desired level above the bottom of the tank. For the 1-f-diameter screen the openings started approximately 1 ft from the bottom of the tank, and 2 in. from the bottom of the tank for the 3-in.-diameter screens. Several of the commercial screens tested were extended in length by adding a section of 10-in.-diameter pipe. For the commercial screens a correction had to be made for the difference in piezometric head to account for the change in velocity head inside the pipe resulting from the reduction in diameter.

The testing procedure consisted primarily of measuring the difference of piezometric head between the inside and the outside of the well screen at a number of points for various discharges. Discharges of $\frac{1}{8}$ cu ft per sec to 2 cu ft per sec for the 12-in.-diameter screens and $\frac{1}{32}$ cu ft per sec to $\frac{1}{8}$ cu ft per sec for the 3-in.-diameter screens were obtained by adjusting the outlet valve. Continuous readings of the gages were taken until only normal fluctuations in the water level existed. This condition was considered to exist when five consecutive readings were consistent. The average of these five readings was used for the analysis. The difference in piezometric head between the inside and the outside of the screen, at any point, was considered to be the difference in head between the inside point and the head outside the 30-in.-diameter screen.

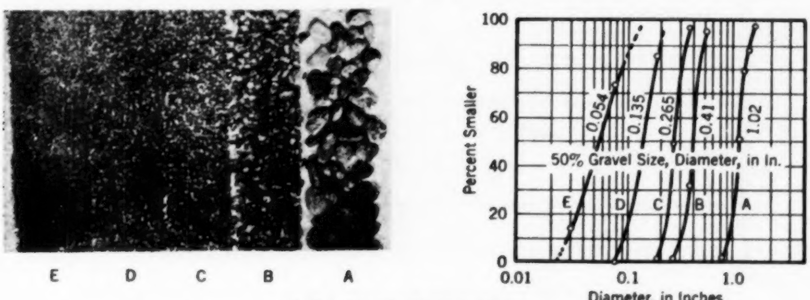


Fig. 5.—Gravel Used in Tests

A series of tests was made for various lengths of the idealized screens. These lengths were obtained by covering part of the perforated area with plastic sheeting and taping the edges to prevent leakage. In all cases the screen was shortened from the top so that the same piezometer always registered the head at the lower end of the screen. Only one length, approximately 2 ft, was tested for the commercial well screens.

When a gravel envelope was placed around the screen, piezometers were located between the envelope and the screen. The difference in piezometric head, in this case, was considered to be the difference between the reading registered by these piezometers and those located inside the screen.

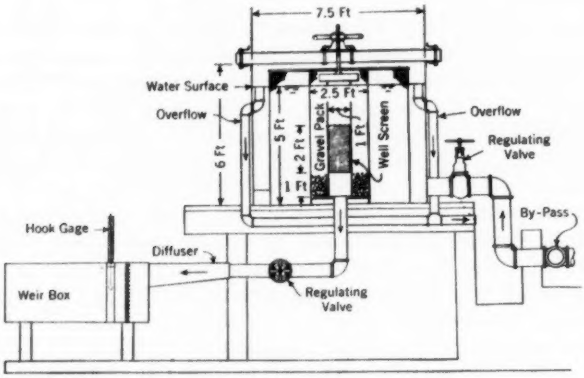
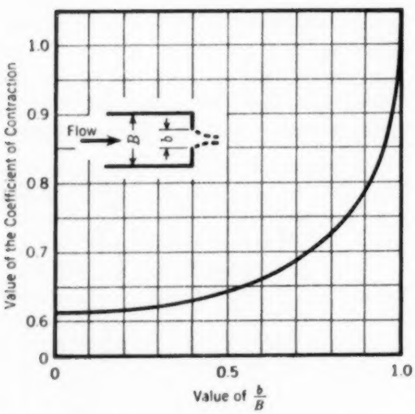


Fig. 6.—Test Apparatus



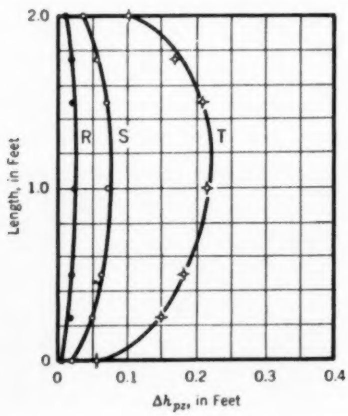


Fig. 7.—Coefficient of Contraction as a Function of the Boundary Geometry

Fig. 8.—Difference in Piezometric Head Between Inside and Outside of Gravel Envelope for Screen A-b and Gravel Size C

Discussion of Results

In Fig. 2, there are shown the theoretical curves obtained from Eq. 15 and the experimental data obtained from the idealized screens when not surrounded by gravel. It should be recalled that these data were taken for the purpose of establishing the validity of Eq. 15. The data were computed from direct measurements. Values used for C_c were determined[7] from Fig. 7.

A satisfactory agreement of the experimental data with the theoretical development is apparent for a large part of the range investigated (Fig. 2). Deviations from the theoretical curve do exist, however, especially at each end of the range—that is, for large values of $\frac{C\,L}{D}$ the loss coefficient becomes asymptotic to a value of approximately 1.2 rather than the theoretical value of unity, and for small values of $\frac{C\,L}{D}$ the experimental data fall below the theoretical curve. As would be expected, if these deviations are a result of the assumptions used in the theoretical development, an analysis of the assumed conditions might provide an explanation for the deviations and permit the making of corrections.

The assumptions most probably in error are that: (1) The piezometric head on the outside surface of the screen is the same at every point; (2) the coefficients of contraction determined by Mr. von Mises apply for flow through the

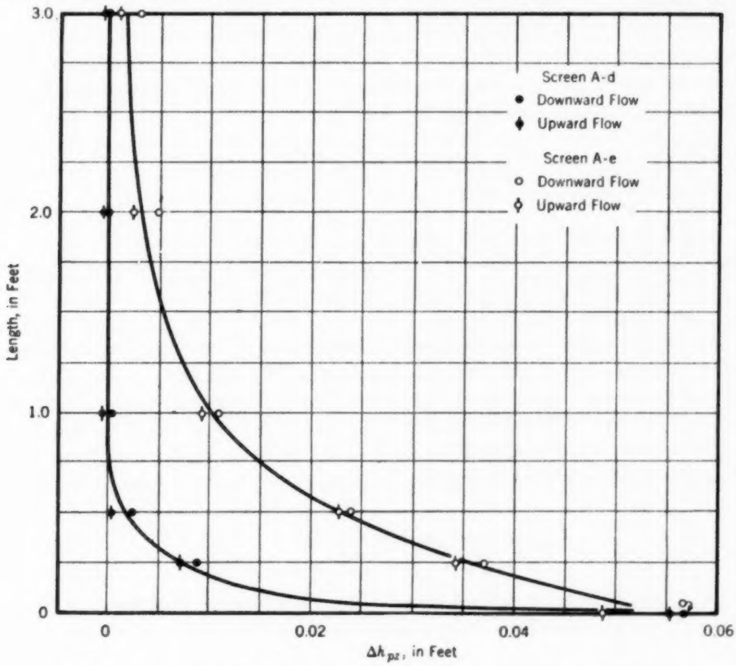


Fig. 9.—Comparison of Differential Head Distribution for Upward and Downward Flow, Screens A-d and A-e

individual orifice openings in the idealized screens; and (3) the effective cross-sectional area of the screen, or area over which uniform velocity may be considered to exist, is the total cross-sectional area of the screen.

The first assumption is of major importance since the basic development is dependent on a constant piezometric head over the outside surface of the screen. The variation of this head was not sufficiently great to permit measurement in the laboratory for screens tested without a gravel envelope. However, a variation (illustrated by Fig. 8) did exist when the screens were surrounded with gravel. In Fig. 8 curve R is drawn for a discharge of 0.248 cu ft per sec, curve S is drawn for a discharge of 0.501 cu ft per sec, and curve T is drawn for a flow of 1.001 cu ft per sec. Curves presented by H. E. Babbitt indicate that this variation is a minor factor for relatively small drawdown in a well.[8] Although

[8] "The Free Surface Around, and Interference Between, Gravity Wells," by H. E. Babbitt and D. H. Caldwell, *Illinois Experiment Station Bulletin 374*, Univ. of Illinois, Urbana, Ill., 1948, p. 60.

conclusive evidence is not available to establish the accuracy of this assumption, the status of the investigation does not warrant the use of a correction for the variation.

It should be noted that the direction of flow (whether upward or downward) is not a factor in causing the deviations from the theoretical curve. Tests (with $Q = 0.0616$ cu ft per sec) made on two of the idealized screens are shown in Fig. 9. Fig. 9 shows that the differential head distribution is the same for either direction of flow.

The use of the coefficients developed by Mr. von Mises would be exact only if the contraction of the jet and the discharge through the openings are independent of the Reynolds number—that is, if the viscous effects of the fluid are insignificant. Many investigations have shown this to be true for high Reynolds numbers, but for low Reynolds numbers the viscous effects do become important.[9] Although a change in C_c (or more accurately C_q of 0.1) is probably

[9] "Elementary Mechanics of Fluids," by Hunter Rouse, John Wiley & Sons, Inc., New York, N. Y., 1946, p. 168.

the largest variation that will occur, it was decided to use a coefficient of discharge as determined by the Reynolds number of the openings. For the purpose of determining C_q the maximum Reynolds number, occurring at the discharge end, was used to obtain the value from Fig. 10.

The third assumption, that of uniform velocity across the entire cross section of the screen, is the one that is most obviously incorrect. The water discharging into the screen has an entrance essentially normal to the longitudinal axis of the screen. This entrance forms a boundary zone along the side of the screen where the flow is normal—rather than parallel—to the longitudinal axis, and in effect reduces the cross-sectional area of the screen. According to M. L.

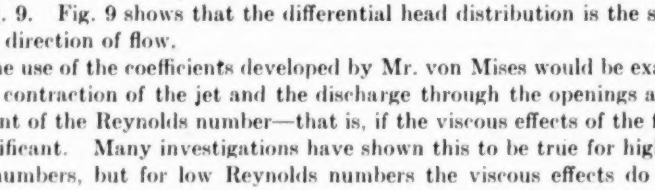


FIG. 10.—COEFFICIENT OF DISCHARGE AS A FUNCTION OF THE REYNOLDS NUMBER

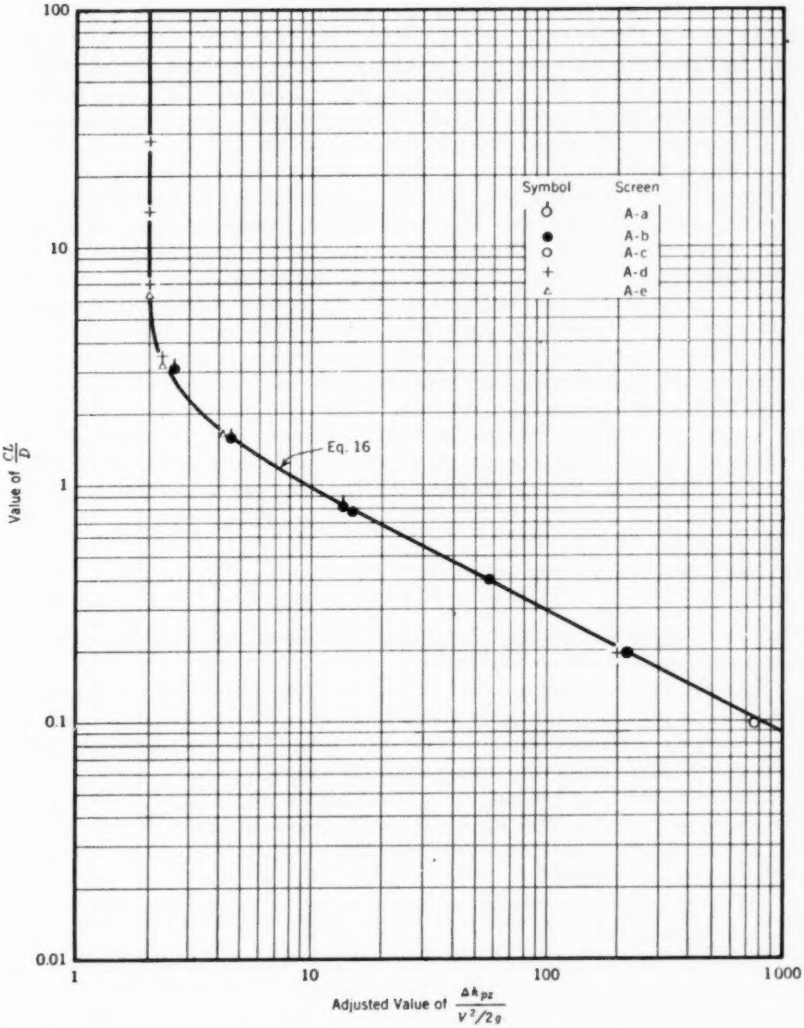


FIG. 11.—ADJUSTED VALUES OF $\frac{\Delta h_{pz}}{V^2/2g}$ AS A FUNCTION OF $\frac{CL}{D}$ FOR TYPE A SCREENS

Albertson, M. ASCE, the distance from the efflux section of a jet (at which point complete mixing with the surrounding fluid takes place) is a function of the jet diameter.[10] This statement applied to the well screen would mean that

[10] "Diffusion of Submerged Jets," by M. L. Albertson, Y. B. Dai, R. A. Jensen, and Hunter Rouse, *Transactions*, ASCE, Vol. 115, 1950, pp. 639-697.

the thickness of the boundary zone would be a function of the size of openings. Other factors (such as the Reynolds number of the screen) would also affect the thickness of the zone. No attempt was made to determine a relationship between the effective diameter of the screen and the several influencing factors. By a trial-and-error method, however, the use of an effective diameter equal to 0.96% of the true diameter was found to give an accurate correction for the screens tested. When the test data were corrected for viscous effects and boundary-zone conditions, the data followed the theoretical curve over the entire range investigated. These corrected data (which indicate that the theoretical development is basically sound) are shown in Fig. 11.

It can reasonably be assumed that Eq. 15 can be used to determine approximate losses for flow into and through commercial well screens. The application of Eq. 15 to commercial screens, however, introduces factors that must be evaluated experimentally for the individual screens. The coefficient of discharge for the openings and the reduction in open area caused by the surrounding aquifer are variables that cannot be measured by direct methods. A screen coefficient, C_s, to account for these factors can be obtained by determining a loss coefficient for the screen from the experimental data, obtaining the $\left(\frac{C\,L}{D}\right)$-value from the theoretical curve shown in Fig. 2, and solving for C_s. This coefficient changes Eq. 14*d* to

$$C = 11.31\ A_p\,C_s \qquad (17)$$

in which C_s replaces C_c and includes the reduction factor for A_p which is necessary when gravel surrounds the screen.

Values of C_s for one set of screens (type B) when not surrounded by gravel are shown in Fig. 12. The curve shows that the coefficient becomes large for small widths of openings—approaching short tube effect—and becomes small for larger widths of openings—approaching the values for a sharp-edged orifice. This variation of C_s could be anticipated from work presented by J. S. McNown, M. ASCE, on screen tests in wind tunnels where the coefficient of contraction was shown to vary with screen thickness and amount of rounding of the upstream edges of the holes.[11]

[11] "Exploratory Tests on Flow Through Screens," by J. S. McNown and M. L. Albertson with D. R. Bianco, P. G. Hubbard, and E. G. Peterson, *Report No. 15*, Iowa Inst. of Hydr. Research, State Univ. of Iowa, Iowa City, Iowa, 1947.

This same method was used to determine C_s for the screens when the screens were surrounded by different gravel sizes. However, the difference in piezometric head at any point inside the screen was considered to be the difference in readings between the piezometer at the point and the piezometer at the center of the screen located between the screen and gravel envelope. These coefficients (shown in Fig. 13) can be applied to Eq. 15 to determine the approximate losses caused by flow into screens. For a particular opening of the type B screens and a specific gravel size in the gravel envelope, a value of C_s can be obtained from the curve which should apply to any length and diameter of screen.

Figs. 14 and 15 show the loss coefficient plotted against the size of gravel in the gravel envelope. It can be seen that the loss coefficient is a constant for most of the screen and gravel combinations tested. The coefficient becomes larger than the minimum value only for the smaller sizes of gravel. Unless the gravel is small enough to reduce the percentage of open area such that $\frac{C\,L}{D}$ is smaller than the critical value, the losses through the screen will be the same for any gravel size and screen opening.

A conversion of potential energy to kinetic energy is required to develop the jet velocity through the perforations of the screen and to accelerate the water along the axis of the screen. This energy cannot be recovered or utilized in the pumping of water from a well. Therefore, both velocities should be kept small to minimize the energy required for pumping.

The velocity of flow within the well varies with the quantity of water pumped. For a given quantity, however, the velocity can be lowered by increasing the diameter of the well. According to Eq. 15 the loss of head (non-usable kinetic energy) varies with several factors, but is at a minimum when $\frac{C\,L}{D}$ is greater than 6. For these conditions the velocity head within the well is

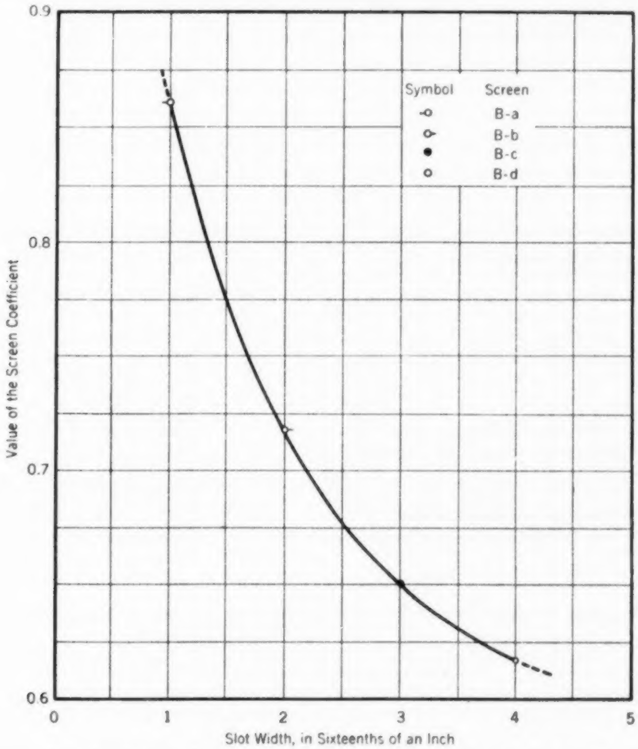


FIG. 12.—SCREEN COEFFICIENT AS A FUNCTION OF THE SLOT SIZE FOR TYPE B SCREENS WITH NO GRAVEL ENVELOPE

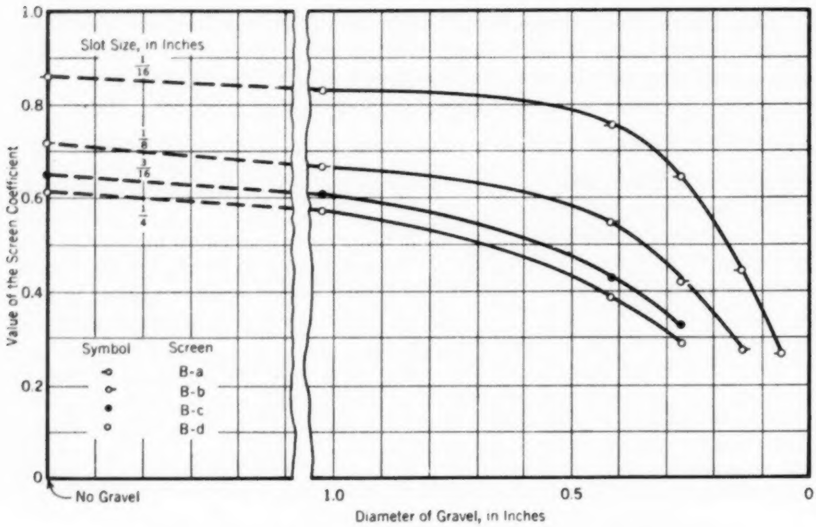
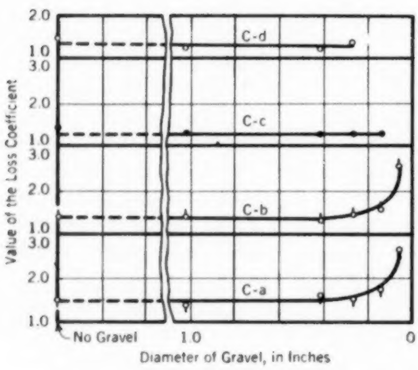


FIG. 13.—SCREEN COEFFICIENT AS A FUNCTION OF THE GRAVEL SIZE



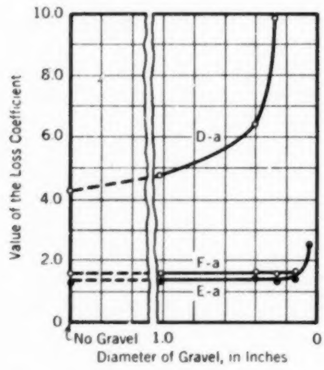


FIG. 14.—LOSS COEFFICIENT AS A FUNCTION OF THE GRAVEL SIZE FOR TYPE C SCREENS

FIG. 15.—LOSS COEFFICIENT AS A FUNCTION OF THE GRAVEL SIZE FOR SCREENS OF TYPES D, E, AND F

approximately equal to the velocity head of the jets. Although increasing the diameter decreases the value of $\frac{C\,L}{D}$, the actual head losses vary directly with V^2: that is, $\frac{C\,L}{D}$ varies inversely with D while the actual head losses vary inversely with D^4. Increasing the diameter may change $\frac{C\,L}{D}$ so that the losses are no longer a minimum for that particular diameter, but they will still be less than the losses resulting from a screen with a smaller diameter.

E. W. Bennison stated that the losses can be decreased by increasing the amount of open area, the length of the screen, or the diameter of the screen.[12]

[12] "Ground Water," by E. W. Bennison, Edward E. Johnson, Inc., St. Paul, Minn., 1947, p. 509.

The theory developed by the writer is strictly in accord with these ideas, with the exception that there is a limit to the amount of reduction in loss of head. This has been shown by Mr. Corey with laboratory tests on well screens of a fixed diameter and length.[5] Mr. Corey found that, for a fixed length and diameter of screen, there is a limiting percentage of open area above which the losses become constant. An examination of Eq. 15 shows that this limit—above which the loss coefficient is constant—could also be reached by changing the other variables. The theory would apply at any point along the screen length, but since a discharge at these points could not be measured, the data used to check Eq. 15 were for the total screen length. According to the theory, the differential head would vary over the length of the screen. This variation is shown in Fig. 16 for 4-ft lengths of screens A-d and A-e. The test on screen A-d was made with $Q = 0.125$ cu ft per sec and the test on screen A-e was made with $Q = 0.126$ cu ft per sec. The value for Δh_{pz} is greatest at the discharge end and decreases with an increase in distance from this end. Since the discharge through the individual openings varies with $\sqrt{\Delta h_{pz}}$ the same type of distribution exists for the discharge into the screen as exists for Δh_{pz}. For a 4-ft length of screen A-d, the value of $\frac{C\,L}{D}$ is greater than the critical value of 6 for lengths greater than 1 ft. Therefore (for screen A-d) the loss coefficient which is proportional to Δh_{pz} is independent of $\frac{C\,L}{D}$ for any length of screen greater than 1 ft.

In Fig. 17 this independence is shown to be true since the curves plotted for total screen lengths of 4 ft, 2 ft, and 1 ft are approximately the same. Fig. 15 shows that the screen A-e must not be less than 4 ft long to be in the constant value range for the loss coefficient. If the length is decreased, the loss coefficient increases as is shown by the curves shown in Fig. 18.

Practical Application

Choosing a well screen for a particular installation is greatly simplified when adequate design criteria are available. It is believed that, with Eq. 15 as a basis, the logical selection of a screen can be made. It can be seen that the major criterion for minimum losses (or drawdown in a well) is that $\frac{C\,L}{D}$ must be equal to or greater than 6. The conditions existing in the field are so variable that a set procedure cannot be specified.

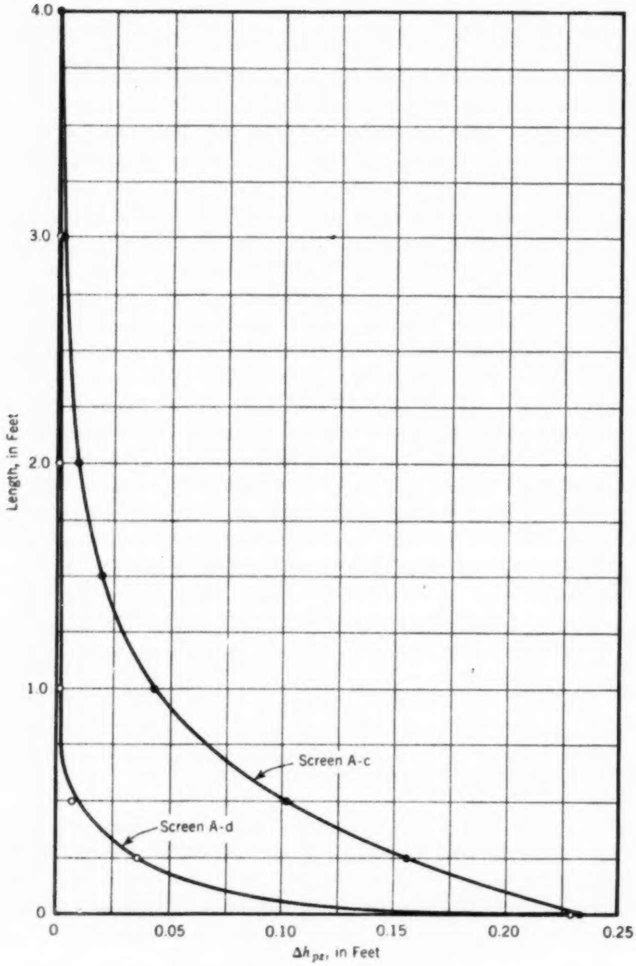


FIG. 16.—DIFFERENCE IN PIEZOMETRIC HEAD BETWEEN THE INSIDE AND THE OUTSIDE OF SCREENS A-d AND A-e

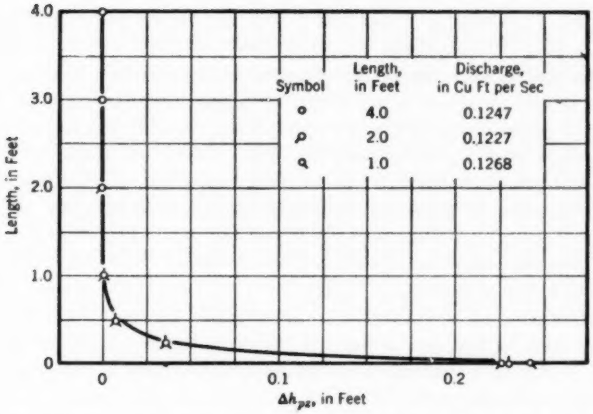


FIG. 17.—DIFFERENTIAL HEAD DISTRIBUTION FOR VARIOUS LENGTHS OF SCREEN A-d

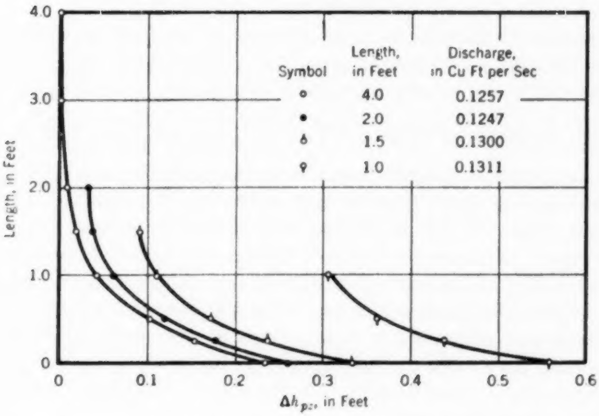


FIG. 18.—DIFFERENTIAL HEAD DISTRIBUTION FOR VARIOUS LENGTHS OF SCREEN A-e

Items to be considered in installing a well are (in addition to those listed under the heading "Theoretical Development") (1) the depth of the water-bearing formation; (2) the size of the openings in the screen; (3) the size of the gravel in the gravel envelope or surrounding formation; (4) the type of pump and location of pump bowl and suction pipe inlet; and (5) the approximate lift or proposed maximum drawdown in the well. Many of these variables are predetermined by factors such as (*a*) existing geological conditions, (*b*) availability of equipment and material, or (*c*) economic considerations. The length of the screen is usually determined by these factors. The diameter may or may not be predetermined; in either case, the effective diameter would depend on the location of the pump bowl. If the bowl is located near the bottom of the well, the diameter must be corrected to account for the reduction in cross-sectional area caused by the riser pipe. If the bowl is located above the perforated section, however, a correction is not necessary unless the suction pipe extends into the perforated section. With the diameter and length of the screen determined, a specific screen can be checked to see if it meets the established criteria. For this check the percentage of open area must be known and a C_s-value for the screen and gravel size must be obtained from a curve such as is shown in Fig. 13. The possibility exists that a specific type of screen must be used to control sand movement or to support the surrounding formation. In this case the diameter of the well—or possibly the length of the screen—could be varied to obtain a value of $\frac{C\,L}{D}$ of 6 or greater.

Eq. 15 also provides a method of checking the head losses incurred by flow through the screen and in the well. This loss might be a major design factor, especially for wells of small diameter.

The variation of discharge into the well can have important significance in certain installations. The laboratory tests indicate that practically all the flow into the well takes place only through the length of screen, from the discharging end, necessary to obtain a $\left(\frac{C\,L}{D}\right)$-value of 6. Although this test result may not prove completely accurate in the field, the same pattern should exist. Better screens could thus be used at the discharge end of the well (the discharge end would depend on the location of the pump bowl and the end of the suction pipe). The use of screens of different material in the well would be of great importance where corrosion is likely to occur, and cost considerations do not permit installation of corrosion resistant screens for the entire length. Since the maximum difference in head occurs at the suction-pipe intake, the velocity through the screen in this region will be greatest, and, consequently, excessive movement of sand is liable to occur there. This fact must be realized when choosing the well screen.

Conclusions

Design criteria resulting from Eq. 15 can be summarized as follows:

1. For minimum screen losses, $\frac{C\,L}{D}$ must be greater than 6.

2. If $\frac{C\,L}{D}$ is greater than 6, the losses through the screen are independent of gravel size. Therefore, the size of gravel in the gravel envelope can be selected on the basis of sand-flow control.

3. When $\frac{C\,L}{D}$ is greater than 6, the actual head loss for a given discharge depends only on the diameter of the screen. This loss can be determined from Eq. 15 and kept to an allowable value by increasing the screen diameter. Increasing the diameter may reduce the value of $\frac{C\,L}{D}$ below *6*; in this case the loss will no longer be a minimum, but when this occurs $\frac{C\,L}{D}$ can be increased by using a longer screen.

4. The greater part of the flow into a well takes place over the length of screen (measured from the discharging end) required to obtain a $\left(\frac{C\,L}{D}\right)$-value of 6. The quality of this section of screen is therefore of greater importance than the rest of the screen.

Screen coefficients available are limited to a few selected screen and gravel size combinations. For the criteria to be of greatest practical value to the well driller, a large extension of the available coefficients is necessary. The principal value of this study, however, is that it calls attention to hydraulic properties of well screens which are not generally known, but which must be given consideration if the best results are to be obtained.

Acknowledgment

The experimental investigation was conducted in the Hydraulic Laboratory of Colorado Agricultural and Mechanical College at Ft. Collins. This paper covers part of a comprehensive investigation of well screens sponsored by the Colorado Agricultural Experiment Station of the college and the Division of Irrigation of the Soil Conservation Service, United States Department of Agriculture, in cooperation with well screen manufacturers and well drilling companies.

APPENDIX

The following symbols, adopted for use in this paper and for the guidance of discussers, conform essentially with "American Standard Letter Symbols for Hydraulics" (ASA Z10.2—1942), prepared by a committee of the American Standards Association with Society representation, and approved by the Association in 1942:

A = cross-sectional area;

A_p = percent of the total area of a well screen that is open area;

C = coefficient defined by Eq. 14*d*;

C_c = coefficient of contraction;

C_q = coefficient of discharge;

C_s = well-screen coefficient depending on the screen and the gravel envelope;

D = diameter of the well screen;
F_y = difference in momentum;
g = acceleration of gravity;
h_{pz} = piezometric head inside the well screen;
Δh_{pz} = difference in piezometric head between inside and outside of a well screen;
$\Delta h'_{pz}$ = difference in piezometric head between the inside and the outside of a well screen at the end which no flow passes;
k = roughness factor for the inside walls of the well screen;
L = length of the perforated section of the well screen;
P = hydrostatic pressure;
Δp = difference in pressure between the inside and the outside of a well screen at a point of the well screen;
Q = quantity of flow, parallel to the screen axis, past a given section inside the well screen;
V = average velocity parallel to the longitudinal axis inside a well screen;
v = velocity of flow through the openings;
z = distance from a datum;
γ = specific weight;
μ = coefficient of dynamic viscosity; and
ρ = density.

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a. Beginning with "Proceedings-Separate No. 200," published in July, 1953, the papers were printed by the photo-offset method.

b. Presented at the Miami Beach (Fla.) Convention of the Society in June, 1953.

c. Presented at the New York (N.Y.) Convention of the Society in October, 1953.

d. Beginning with "Proceedings-Separate No. 290," published in October, 1953, an automatic distribution of papers was inaugurated, as outlined in "Civil Engineering," June, 1953, page 66.

e. Discussions, grouped by divisions.

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